BULLETIN

OF THE INSTITUTE OF METALS

VOLUME 3 AUGUST 1956 PART 12

INSTITUTE NEWS

Institute's New Headquarters

Third List of Donations

The Council acknowledges with many thanks the following additional generous donations to the funds of the Institute, towards the cost of the purchase of the lease of 17 Belgrave Square, S.W.1, as a new Headquarters of the Institute and of its equipment.

	£	s.	d.
*Tube Investments, Ltd.	3500	0	0
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Brass and Copper Tube Association	1000	0	0
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Jacks, Mr. Stanley	1	1	0
Martin, Mr. A. R.	1	1	0

* Donations under covenant. The amount stated is the total to be received, including the tax recoverable at the present standard rate, where applicable.

Student's Essay Competition

Owing to the disappointing entry for the 1955 competition, it has been decided that no competition shall be held in 1956. The question will be reconsidered next year.

Election of Council for 1957–58

In accordance with the Articles of Association, the following are due to retire from the Council at the 1957 Annual General Meeting: *President:* Major C. J. P. Ball, D.S.O., M.C., F.R.Ae.S. *Past-President:* Professor F. C. Thompson, D.Met., M.Sc., F.I.M. *Vice-Presidents:* L. B. Pfeil, O.B.E., D.Sc., A.R.S.M., F.R.S., F.I.M., and Major P. Litherland Teed, A.R.S.M., F.R.Ae.S., M.I.M.M., F.I.M. *Ordinary Members of Council:* W. A. Baker, D.Sc., F.I.M., E. R. Gadd, F.I.M., and The Hon. John Grimston, M.P.

Under Article 19, Major C. J. P. Ball, D.S.O., M.C., F.R.Ae.S., will fill the vacancy on the Council as Past-President.

In accordance with Article 22, the Council nominates the following members to fill vacancies:

As President:

L. B. Pfeil, O.B.E., D.Sc., A.R.S.M., F.R.S., F.I.M., Director, The Mond Nickel Co., Ltd.; Director, Henry Wiggin and Co., Ltd.

As Vice-Presidents:

The Hon. John Grimston, M.P., Director and General Manager, Enfield Rolling Mills, Ltd., and Director, Enfield Copper Refining Co., Ltd.; Enfield Rolling Mills (Aluminium), Ltd.; Enfield Zinc Products, Ltd.

Marshal of the Royal Air Force the Right Hon. the Lord Tedder, G.C.B., Hon. LL.D., Chancellor, University of Cambridge; Chairman, Standard Motor Co., Ltd.

As Ordinary Members of Council:

Professor J. W. Cuthbertson, D.Sc., F.I.M., Professor of Metallurgy, University of Nottingham.

Sir Ronald Prain, O.B.E., Chairman and President, Rhodesian Selection Trust, Ltd., and Roan Antelope Copper Mines, Ltd.

F. Waine, Director, British Insulated Callender's Cables, Ltd.

Members are reminded that, in accordance with Article 22, any ten members may also at, or before, the business part of the Autumn General Meeting (17–25 September 1956), nominate in writing, with the written consent to act if elected of the person nominated, any duly qualified person other than one of those nominated by the Council, to fill any vacancy on the Council, but each such nominator is debarred from nominating any other person for the same election. If two or more persons are nominated for any honorary office, they (or such of them as are not Ordinary Members of Council who are not retiring at the next Annual General Meeting) will be deemed to have been nominated also for any vacancies among the Ordinary Members of Council. No person is eligible to fill any vacancy at such

Annual General Meeting unless he has consented in writing to be nominated and has been nominated or deemed to be nominated for the same in compliance with this Article.

Election of Members

The following 2 Overseas Sustaining Members, 5 Ordinary Members, 1 Junior Member, and 3 Student Members were elected on 19 June 1956:

As Overseas Sustaining Members

ANACONDA AMERICAN BRASS, LTD., 8th Street, New Toronto, Ont., Canada.

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As Ordinary Members

BERNER, G. Tay, B.A.Sc., General Sales Manager, Anaconda American Brass, Ltd., 8th Street, New Toronto, Ont., Canada.

EVANS, Urda Malcolm, Works Manager, Anaconda American Brass, Ltd., 8th Street, New Toronto, Ont., Canada.

HAMBURGER, J. A., Director, N. V. de Koninklijke Nederlandsche Lood-en Zinkpletterijen voorheen A.D. Hamburger, Leidsekade 30, Utrecht, Netherlands.

MOORE, Eric Joseph, A.M.C.T., A.M.I.I.A., A.I.M., Works Manager, H. J. Enthoven and Sons, Ltd., Darley Dale Smelter, South Darley, Matlock, Derbyshire.

ROBILLARD, André Lucien, Lic.ès Sc., Attaché de Recherches, Centre National de la Recherche Scientifique, Laboratoire de Métallurgie, Ecole Nationale Supérieure des Mines, Paris.

As Junior Member

COULOMB, Pierre François Charles, Lic.ès Sc., Ing. Civ. Mines, M.S. (Met. Eng.), Attaché de Recherches, Centre National de la Recherche Scientifique, Laboratoire de Métallurgie, Ecole Nationale Supérieure des Mines, Paris.

As Student Members

FARMER, Raymond Cedric, L.I.M., Assistant Metallographer, Guest, Keen and Nettlefolds, Ltd., Heath Street, Smethwick.

LEYMONIE, Claude Henri, Ing. E.S.P.C.I., Lic.ès. Sc., Attaché de Recherches, Centre National de la Recherche Scientifique, Laboratoire de Métallurgie, Ecole Nationale Supérieure des Mines, Paris.

MOORE, Nigel Edward Sidney George, Undergraduate, Department of Metallurgy, University College, Swansea.

The following 1 Overseas Sustaining Member, 22 Ordinary Members, and 5 Student Members were elected on 29 June 1956:

As Overseas Sustaining Member

NORANDA COPPER AND BRASS, LTD., P.O. Box 1238, Place d'Armes, Montreal 1, P.Q., Canada.

As Ordinary Members

VAN DEN BERG, Gerard Johan, Dr.Sc., Conservator-Wetenschappelijk hoofd ambtenaar A, Kammerlingh Onnes Laboratorium, Rejksuniversiteit te Leiden.

BIBRING, Hervé, Ingénieur de Recherches, Office National d'Etudes et de Recherches Aéronautiques, 25 Avenue de la Division Leclerc, Chatillon-sous-Bagneux (Seine), France.

BLACK, Duncan Alexander, D.R.T.C., A.I.M., Scottish Sales Engineer, Acheson Colloids, Ltd., 18 Pall Mall, London, S.W.1.

BRANSCOMB, *Professor* Lewis Capers, Jr., A.B., A.M.L.S., Ph.D., Director of Libraries and Professor of Library Administration, Ohio State University, Columbus 10, Ohio, U.S.A.

CLARKE, Derek Ashdown, M.A., A.L.A., Librarian, University College of Rhodesia and Nyasaland, Private Bag 167H, Salisbury, Southern Rhodesia.

DECKER, Raúl Guillermo Antonio, Vice-Presidente, Guillermo Decker S.A., Belgrano 836, Buenos Aires, Argentina.

FARREN, Gerard, General Manager, Irish Steel Holdings, Ltd., Haulbowline, Co. Cork, Eire.

GUARD, Ray W., M.S. (Met.Eng.), Ph.D., Research Metallurgist, General Electric Research Laboratory, Box 1088, General Electric Company, Schenectady, N.Y., U.S.A.

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KOPCZYNSKI, Zbigniew Stanislaw, Dipl.-Ing., M.Eng.Sc., Metallurgist, Société Anonyme des Forges et Usines de Moos, Emmenbrucke, Lucerne, Switzerland.

LAROCCA, Edward William, Staff Metallurgist, U.S. Naval Ordnance Test Station, Inyokern, China Lake, Calif., U.S.A.

PIKE, Edmund John, Group Technical Manager, Almin, Ltd., Almin House, Stoke Poges, Bucks.

PULLEN, Rowland H., Melting Shop Manager, Steel Company of Wales, Ltd., Port Talbot, Glam.

SEBILLEAU, François Edouard Jean, Ing.-Doct., Ingénieur, Office National d'Etudes et de Recherches Aéronautiques, 25 Avenue de la Division Leclerc, Chatillon-sous-Bagneux, (Seine), France.

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UNDERWOOD, Ervin Edgar, B.S. (Met.Eng.), Sc.D., Principal Metallurgist, Battelle Memorial Institute, 505 King Avenue, Columbus 1, Ohio, U.S.A.

WHITE, Jack Lee, B.S., D.I.C., Ph.D., National Research Council Postdoctoral Research Associate in Metallurgy, The Naval Research Laboratory, Washington 25, D.C., U.S.A.

WOOD, Alan John, L.I.M., Metallurgist, The English Electric Co., Ltd., Stafford.

WOODS, Victor H., City Librarian, Birmingham Public Libraries, Reference Library, Birmingham 1.

YAMAGUCHI, Hideo, D.Eng., Chief of the Research Division, Shinko Metal Industries, Ltd., Chofu, Shimonoseki, Yamaguchi Prefecture, Japan.

As Student Members

BRAMAH, David Eric, Undergraduate, Department of Metallurgy, University of Sheffield.

DOWNS, James Joseph, 9th Quartermaster Company, Goeppingen, Germany.

EYRE, John David, Experimental Assistant, Grade 2, Defence Standards Laboratories, Private Bag No. 4, Ascot Vale P.O., Vict., Australia.

GANGULI, Amalendu, B.E., Research Student, Department of Metallurgy, Battersea Polytechnic, London, S.W.11.

HOWARD, John Edward, Undergraduate, Department of Metallurgy, University of Sheffield.

RADIATION DAMAGE TO METALS AND ASSOCIATED PROBLEMS *

THE EFFECT OF NEUTRON IRRADIATION ON THE MECHANICAL PROPERTIES OF METALS

By M. J. MAKIN, B.Sc., Ph.D.

Previous Work

NUMEROUS reports in the published literature indicate that the resistance of metals to deformation is markedly increased by irradiation with fast particles. In the majority of the experiments so far carried out, this resistance has been determined by measurements of the indentation hardness, which are easy to perform on active specimens. Billington and Siegel [1] found that the hardness of copper, beryllium copper, stainless steel, Monel, 65 : 35 brass, and silicon bronze were increased by pile irradiation, the increase in hardness of copper being much greater in the annealed than in the cold-worked condition.

Geib, Harmon, and their co-workers [2-4] studied the effect of deuteron irradiation on the hardness of molybdenum. An increase in hardness was observed in annealed specimens, but the experiments were not very conclusive, as there was a large scatter in the results. It is also likely that some chemical reaction was proceeding during the irradiation, as the specimens became covered with an unidentified surface film which appeared to be removed by trichlorethylene, but which may have exerted an influence on the results. A similar phenomenon has been observed by the present author on molybdenum cooled by an air blast during irradiation with electrons.

To distinguish between thermal-spike and point-defect effects, Dixon and Meechan [5] irradiated copper with 1·25-MeV. electrons at —20° C. Tukon hardness measurements showed an increase from 43·3 to 47·7 V.P.H., which annealed out in two roughly equal stages, one between 0° and 100° C. and the other between 200° and 300° C.

Murray and Taylor [6] found that the hardness of a large number of solid-solution copper alloys increased by 10–20 V.P.N. on neutron irradiations of $1–2 \times 10^{18}$ fast nvt.† Beryllium copper, however, increased in hardness by ~40 V.P.N. and annealing studies showed that the corresponding increase in resistivity recovered before the hardness.

Sutton and Leeser [7] and Leeser [8] have reported the effect of neutron irradiation on the hardness of a wide variety of engineering materials. Typical increases in hardness of annealed materials after 10^{19} nvt were: plain carbon steels 50, stainless steels 110, nickel 160, zirconium 90 B.H.N. The increases observed in hardened materials were smaller, depending on the amount of hardening to which they had been subjected before irradiation.

Blewitt and Coltman [9] investigated the effects of pile irradiation on the critical shear stress and stress/strain curves of copper single crystals. The first tests showed that the critical shear stress of a specimen irradiated with a fast neutron dose of $1·8 \times 10^{18}$ nvt increased from 0·24 to 1·94 kg./mm.^{2} when tested at room temperature. When the testing temperature was lowered to 78° K., the critical shear stress of the irradiated specimen was further increased, and the initial rate of work-hardening was decreased, so that the curves for the irradiated and unirradiated specimens merged after about 20% strain. Jamison and Blewitt [10] showed that the appearance of slip lines was altered by previous pile irradiation, the fine slip lines in pure copper being replaced by clusters of coarser lines similar to those observed in α-brass.

Redman, Coltman, and Blewitt [11] studied the recovery of the critical shear stress after irradiation. Between 300° and 400° C., complete recovery occurred with an activation energy of 2·2 eV., the same energy as that for self-diffusion. The relaxation time varied from 400 hr. at 305° C. to 11 min. at 385° C. No recrystallization was found, despite the large increase in critical shear stress.

McReynolds, Augustyniak, McKeown, and Rosenblatt [12] have observed increases of several hundred per cent. in the critical shear stress of copper and aluminium single crystals after neutron bombardment below —150° C. Annealing experiments showed that the increase annealed out between 300° and 400° C. in copper, together with the remaining resistivity increase, while in aluminium both properties recovered between —80° and —20° C. The activation energies were 2 and 0·55 eV., respectively.

Kunz and Holden [13] have shown that the yield stress of iron and zinc single crystals is markedly increased by neutron irradiation at room temperature. No change was observed in lead crystals, however, probably because of the low annealing temperature of lead. Annealing tests on the iron crystals between 200° and 500° C. gave an activation energy for recovery of 3·1 eV., which is the same as that for self-diffusion in iron. The effect of previous cold work on the irradiation hardening of iron single crystals has been measured by Kunz.[14] The percentage increase in yield stress on irradiation decreased rapidly with increasing previous extension, becoming zero

* Papers forming the basis of an Informal Discussion organized by the Metal Physics Committee of the Institute of Metals and held in connection with the Autumn Meeting at Buxton, on 22 September 1955. The papers were contributed by members of the staff of the Atomic Energy Research Establishment, Harwell, Berks.

† The unit nvt is used to measure the integrated flux in neutrons/cm.^{2}.

after an extension of 17% before irradiation. Iron crystals hardened before irradiation by solid-solution alloying with carbon hardened on irradiation in much the same way as pure crystals, i.e. the effects of solid-solution hardening and irradiation hardening are additive.

Kelly [15] has studied the structure of slip bands in aluminium bombarded with α particles at $-100°$ C. Electron micrographs of irradiated specimens tested at $-196°$ C. showed an increase in the amount of slip on a given plane, as compared with unirradiated specimens.

Sutton and Leeser [7] and Leeser [8] have presented tables showing the effect of doses up to about 3×10^{20} thermal neutrons (1×10^{20} fast), at temperatures from 20° to 250° C., on the ultimate tensile strength and elongation of a number of steels, nickel- and cobalt-based alloys, zirconium, tungsten, tantalum, and some of their alloys. Typical figures for the increase in tensile strength are: plain carbon steels 15,000, stainless steels 25,00, nickel 45,000, and zirconium 5000 lb./in.^{2}. The yield strengths are raised about twice as much as the ultimate tensile strengths. The results indicate that softer materials exhibit greater hardening on irradiation than harder materials, and that the effects tend to saturation at high doses. The elongation before fracture is reduced by the irradiation, but the decreases are moderate, in most cases by about one-fifth to one-third. Other properties studied were the impact behaviour of some boiler steels, the density of steels and nickel and cobalt alloys, and the magnetic susceptibility and electrical resistivity of steels. The transition temperature of boiler steels is raised by irradiation, the amount depending upon the type of steel. The magnetic-susceptibility measurements showed that there is some transformation from austenitic to ferritic steels during irradiation, though the amount transformed is insufficient to affect the corrosion-resistance of the more common stainless steels.

The embrittlement of molybdenum by neutron irradiation has been observed by Bruch, McHugh, and Hockenbury.[16] Doses of between 1·9 and 5·9 $\times 10^{20}$ nvt raised the ductile $\rightarrow$ brittle transition temperature from $-30°$ to $+70°$ C., and hence the material was completely brittle at room temperature after irradiation. Bruch *et al.* showed that although both the flow-stress/temperature curve and the fracture-stress curve were affected, the former was raised much further, causing the increase in transition temperature.

Meyer,[17] who studied the effect of deuteron bombardment on the notch sensitivity of mild steel, showed that the ductile $\rightarrow$ brittle transition temperature was raised from $-1°$ to 18° C. Annealing out occurred between 260° and 480° C., with a variable activation energy.

Steele and Wallace [18] studied the effect of neutron bombardment on the stress/strain curves of a series of aluminium alloys in the annealed, strain-hardened, and aged conditions. They found that both the yield stresses and the ultimate tensile strengths of all the specimens rose, the magnitude of the increases being greatest in the annealed specimens. The reduction in ductility of irradiated annealed specimens was much less than that of unirradiated specimens strain-hardened to the same yield stress. The ductility of some of the strain-hardened specimens actually increased on irradiation. The strain-hardening exponent (i.e. the best power-law fit to the true stress/strain curve) was greater for the irradiated specimens, indicating that the hardening rate had decreased.

Konobeevsky, Pravdyuk, and Kutaitsev [19] have reported Russian work on the effect of neutron bombardment on the hardness, tensile strength, ductility, and microstructure of a number of metals. Increases in hardness and tensile strength were observed and also some change in the microstructure. The grain-size of copper and nickel increased, and zirconium became heavily twinned and partially recrystallized during the irradiation, which was carried out at between 250° and 300° C. Unfortunately, however, control specimens were not used, so that it is not possible to determine whether these are genuine irradiation effects or are due to long soaking at the irradiation temperature. The increase in hardness during irradiation of copper and stainless steel was observed to be independent of the amount of previous deformation, although the irradiation hardening of Armco iron decreased rapidly with previous work.

Experiments on Polycrystalline and Single-Crystal Metals

At the Atomic Energy Research Establishment, the present author has attempted a more systematic investigation of the effect of neutron irradiation on the mechanical properties of both polycrystalline and single-crystal metals than has hitherto been made. Polycrystalline copper, nickel, titanium, zirconium, and molybdenum have been tested at various temperatures after pile irradiation with 5×10^{19} nvt at about 100° C. The copper and nickel were fully annealed before irradiation, and the other metals were studied under conditions similar to those in which they might be used.

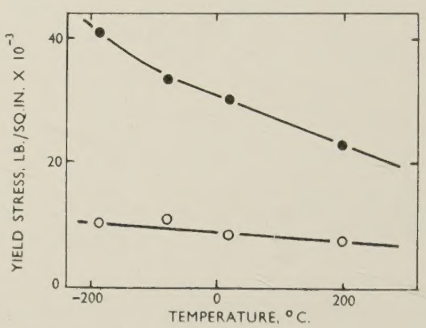

FIG. 1.—Variation of Yield Stress with Temperature for (●) Irradiated and (○) Unirradiated Copper.

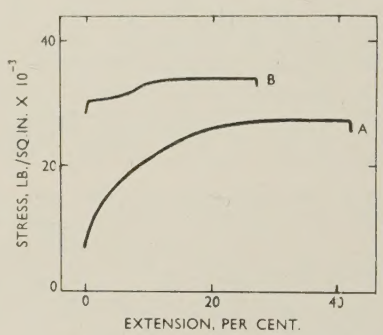

FIG. 2.—Stress/Strain Curves for Copper at Room Temperature, (*A*) Before and (*B*) After 5×10^{19} nvt Irradiation.

Increases in the yield stress and the ultimate tensile strength were observed for all the metals studied, the magnitude depending markedly upon the testing temperature, being very much greater at lower temperatures. The variation of yield stress with testing temperature for irradiated and unirradiated copper is shown in Fig. 1. This effect is reversible and is not due to annealing at the higher temperatures. The stress/strain curves for copper at toom temperature are shown in Fig. 2. A

yield point was introduced by the irradiation in all the specimens tested, and the elongation to fracture was reduced by about the same amount at all temperatures. The effect of previous cold work on the irradiation hardening has been studied for copper (Fig. 3); previous tensile deformation diminished the increase in yield stress upon subsequent irradiation.

Annealing experiments have been carried out on copper and nickel; in copper the yield stress annealed out between 300° and 350° C. with an activation energy of 2·05 eV., while in nickel annealing out occurred between 340° and 400° C. with

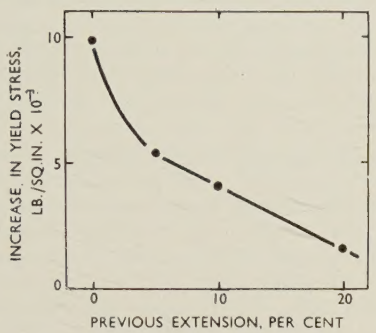

FIG. 3.—Effect of Previous Cold Work on Increase in Yield Stress of Copper After 5×10^{18} nvt Irradiation.

an activation energy of 2·64 eV. The recovery of nickel appeared to proceed approximately 100 times faster than that of copper for the same exponential term.

Experiments on copper single crystals have shown that the critical shear stress increases markedly for only very small neutron doses ($\sim 10^{16}$ nvt) and that the rate of increase rapidly diminishes with increasing dose. The critical shear stress of irradiated crystals is markedly dependent upon the testing temperature, in a similar manner to the yield stress of polycrystals. The characteristics of the stress/strain curve are much altered by the irradiation, the amount of easy glide being considerably increased at the lower testing temperatures. The appearance of the slip lines is also considerably altered, the very many fine lines in the unirradiated crystal being replaced by clusters of coarser lines.

The interpretation of these effects is not at all clear at the present time. It is certain that they are not due to isolated interstitial atoms and vacancies, but to some annealed configuration of these defects, since work on the recovery of electrical resistivity of copper after irradiation at low temperatures has shown that point defects are mobile below room temperature, whereas the changes in mechanical properties remain up to 300° C. Various suggestions which can be put forward include the formation of: (i) Brinkman displacement spikes, (ii) agglomerates of interstitial atoms forming small platelets between existing crystal planes, (iii) Cottrell atmospheres of interstitial atoms or vacancies around dislocations, and (iv) jogs on edge dislocations due to the condensation of interstitial atoms or vacancies. Each of these possibilities is capable of accounting for some of the experimental facts, although each one is open to various objections. It is possible that some combination of the above theories will eventually provide the best explanation.

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RADIATION DAMAGE IN IONIC SOLIDS

By J. H. O. VARLEY, B.Sc., Ph.D., MEMBER

Introduction

A STUDY of the fundamental processes occurring in ionic solids under irradiation has its most obvious application in the field of ceramics; nevertheless, it has a limited application in discussing the behaviour under irradiation of metals normally used in engineering design.

The presence of intermediate phases of greater or lesser ionic character in commercial alloys would seem to merit an understanding of fundamental mechanisms causing radiation damage in ionic solids. However, this is probably of somewhat academic interest, for the following reasons. Radiation damage changes the mechanical properties of materials; the intrinsic mechanical properties of intermediate phases are usually poor from an engineering standpoint, and radiation damage will consequently produce a small relative effect. Moreover, these phases are normally distributed in a commercial alloy in a manner which is not detrimental to the mechanical properties of the alloy as a whole. Consequently, radiation damage in such intermediate phases will probably produce only a small effect on the mechanical properties of alloys containing them; damage in the ductile matrix will be the major result.

The corrosion behaviour of metals under irradiation necessitates a background knowledge of the effects of radiation on ionic materials. The mechanism underlying the corrosion of

metals is that of the transport of electrons and ions through the crystal lattice of (or along surface cracks in) the corrosion product and surface oxide layers. A slow corrosion rate implies a low transport rate for the electrons and ions participating in the chemical reaction. Thus oxidation rates, for instance, may be slow because the oxide film, through which transport must take place, is a poor electronic conductor, as in the case of aluminium/aluminium oxide. Furthermore, the transport of ions may occur through the movement of ions amongst interstitial sites in the lattice, or alternatively, through the presence of vacant lattice sites which enable metal ions to move up through the lattice to the air interface, or conversely enable oxygen ions to move towards the metal/oxide interface.

The oxide layer protecting the metal surface will be ionic in character to an extent depending upon the detailed distribution of valence electrons between the metal and oxygen ions.

Radiation in such an oxide lattice can possibly change the oxidation rate for the following reasons. The damage induced consists of atoms or ions displaced from their normal lattice sites into interstitial positions in the lattice. Depending upon the activation energy for movement of interstitial ions, there will be some temperature above which these displaced ions can wander relatively quickly through the lattice, and under such conditions these ions or atoms will either be restored to their normal lattice sites, or alternatively, be trapped at vacant lattice sites of the wrong kind (e.g. an oxygen atom trapped at a vacant metal-ion site) or at dislocations. As a result of such processes, the distribution of atomic defects (interstitial atoms or ions and vacant lattice sites of each kind, positive and negative ion vacancies) may be expected to differ, in the oxide layer when under irradiation, from the distribution in an unirradiated specimen under otherwise similar conditions, viz. temperature and previous history.

Radiation damage in ionic solids may also change the contribution to the electrical conductivity from the free electrons within the crystal. Electrons are excited from their normal energy levels into traps at higher energies. For instance, in alkali-halide crystals, such as sodium or potassium chloride, electrons can be excited by X-radiation and higher-energy ionizing radiation into lattice vacancies where a halogen ion is missing. Electrons in these traps can be excited by photons with energies in the visible light range, and such crystals consequently appear coloured. These trapped electrons, when excited to higher energies, may wander through the crystal and contribute to the electrical conductivity of the material. Electrons thus freed from traps may recombine with the ions from which they were ejected by the initial ionizing radiations, provided that these ions, which are short of electrons, have not themselves been displaced and occupy normal lattice sites. If, however, the atoms complementary to the trapped electrons have been so displaced and are trapped either interstitially or at sites of the wrong kind or, again, at dislocations, then recombination between the trapped electrons and these atoms to reform negative ions may not be possible. In this latter event, radiation will have produced electrons within the lattice which may possibly contribute to the electronic conductivity of the crystal, and a redistribution of lattice defects resulting from the displacement of atoms which may alter the ionic contribution to the electrical conductivity.

It is plausible, therefore, that radiation will alter the resistance of a given metal towards oxidation and corrosion in general, as a result of physical changes in the protective film covering the metal, and quite apart from those induced by the radiation in the corrosive medium. The direction of the change will depend upon the details of the corrosion mechanism. From these arguments it will be seen that a dominant factor in determining the extent to which the properties of the film are changed is the efficiency with which ions are displaced by radiation.

The Displacement of Ions in Ionic Lattices

A convenient way of studying this efficiency, i.e. the number of displaced atoms produced per unit flux, where flux is the number of high-energy particles (electrons, X-ray photons, γ-rays, &c.) incident per unit area of specimen, is to observe the optical absorption produced in ionic crystals. Since a certain amount is known about the optical absorption resulting from electrons trapped at negative ion vacancies in alkali-halide crystals such as potassium chloride, this material has been studied.

Crystals were bombarded with high-energy electrons, when they became coloured to some given depth below the incident surface, dependent upon the incident electron energy ($\sim$1 MeV.). The crystals were then optically bleached at room temperature by standing them in daylight, whereupon some of the colour disappeared. The part of the colour which can be so bleached is attributed to the removal of electrons trapped at negative ion vacancies, the so-called *F*-centres, by light photons with energies corresponding to wave-lengths in the visible spectrum. The electrons thus removed from these traps recombine with chlorine atoms, which have not been displaced and occupy normal lattice sites, to re-form chlorine ions.

Some of the coloration could not be removed, and this is attributed, as discussed above, to the chlorine atoms complementary to the trapped electrons having been displaced by the radiation and trapped at sites where recombination with electrons to form ions is not possible. A measure of the number of absorption centres can be obtained by measuring the optical absorption of the *F*-band and hence, on the above interpretation, a lower limit to the number of ions displaced can be estimated. It has been found experimentally that the average number of chlorine ions displaced per unit flux in unit volume of irradiated (coloured) crystal is of the order of 100.

If displacements were brought about by direct momentum transfer from the fast electrons to the stationary ions in the crystal, the (calculated) average number of displaced ions in unit volume per unit flux would be of the order of 3. There is, then, a serious discrepancy between observed experimental values for the efficiency of displacement and that calculated for displacement by momentum transfer. Some other displacement mechanism must therefore be sought, and this will now be briefly outlined.

Ionizing radiation, such as X-ray, or γ-ray, produces fast electrons within the solid; alternatively, the fast electrons may be incident upon the specimen from an external source, as in the experiments described. These high-energy electrons lose a large fraction of their energy by inelastic collisions with electrons bound to the ions in the lattice. Energy is thus transferred to these latter electrons, and if a given electron receives sufficient energy it is removed from the ion. There is an appreciable probability that more than one electron will be removed from a given ion, and if the ion is a negative ion the temporary state after the multiple ionization process is complete is one where a positive ion (multiply-ionized negative ion) is in a lattice site of the wrong kind, for the electrostatic potential favours the presence of a negative ion at this site. The electrostatic forces assisted by thermal vibrations may then eject the ion from the lattice site into an interstitital position. The magnitude of the force tending to eject the ion will depend upon the degree to which it has been ionized, and the probability that the ion will in fact be ejected will also depend

upon the displacement energy necessary to force the positively charged ion between neighbouring ions. Thus, a large value of the displacement energy will demand a large force to eject the ion, and this in turn will necessitate a high degree of ionization.

The probability of removing more than one electron from a given ion decreases by a factor between 10 and 100 for each additional electron removed, but even so, the efficiency of this displacement mechanism can be high enough to account for the experimental observations, and an approximate calculation indicates that the number of electrons which must be removed from a negative chlorine ion in KCl is three, in order that it be displaced. This number is deduced from the observation that, on the average, 100 ions are displaced in unit volume of coloured crystal per unit flux. A further rough calculation suggests that the displacement energy must lie between 15 and 30 eV., which is in keeping with displacement energies observed in other materials. If the displacement energy is large, then the multiple ionization-displacement mechanism loses its advantage over the mechanism of displacement by direct momentum transfer.

Thus, in favourable cases, atomic displacements may occur in ionic crystals through the multiple ionization of negative ions, and this latter process can be effected by electrons with energies too small to produce displacements by direct momentum transfer. In particular, displacements may be brought about in some crystals under the influence of X-radiation which produces photoelectrons internally within the crystal.

CHANGES IN THE PROPERTIES OF URANIUM DURING BURN-UP

By S. F. PUGH, M.A., A.I.M., Member

Introduction

Natural uranium contains about 0·7% U^{235} which undergoes fission when it absorbs thermal neutrons. Most of the energy released during fission is associated with the fission fragments that leave the site of fission with a high velocity. It has been calculated that a pair of fission fragments will displace about 10^5 uranium atoms from their lattice sites in their motion through the lattice before coming to rest.[1,2] Neutrons are also emitted during fission with an energy of 2 MeV. In a thermal reactor the neutrons lose their energy by collision with atoms of the moderator, until they are left with only sufficient energy to keep them in equilibrium with the thermal oscillations in the moderator material, namely about 1/40 eV. Any fast neutrons that travel through structural material in the pile will displace atoms and so alter the properties of the structural materials, just as they cause changes in the structure of the moderator if the latter is a solid. A fission neutron having an energy of 2 MeV. can displace about 2000 atoms in a structural material such as copper before losing all its energy;[3] this is about twenty-five times smaller than the number that could be displaced by a fission fragment. The neutrons have a large mean free path in the pile and lose most of their energy in the moderator, whereas the mean free path of the fission fragments is about 10^{-3}–10^{-4} cm., so that they lose most of their energy in the uranium. Therefore, the greater part of the damage in the uranium is due to the fission fragments and not to the fast neutrons.

The atoms displaced from their lattice sites by the fission fragments do not all return to their original positions, and so changes occur in the physical and mechanical properties of the uranium. In uranium at room temperature these changes are effectively saturated at a burn-up * of about 10^{-5}. At a burn-up of about 10^{-4}, growth and wrinkling in uranium become sufficiently great to affect the running of a reactor, so that study of these phenomena has had great technological importance.

At a burn-up of 10^{-3}, effects due to the mere presence of the fission fragments become troublesome, particularly at high temperatures, since more than 10 wt.-% of the fission products are the inert gases xenon and krypton, while some of the remainder are non-metals.

The following sections contain interesting examples of the types of damage that can occur, but the treatment is not exhaustive.

Changes in Mechanical Properties

The hardness of annealed uranium increases [4] on irradiation from about 215 to 275 V.P.H. for a burn-up of 10^{-4} and to 315 V.P.H. at 10^{-3} burn-up. The changes in mechanical properties in uranium probably take place by mechanisms similar to those occurring in non-fissile materials under fast-neutron irradiation.[5] Fig. 1 shows stress/strain curves of polycrystalline uranium wires before and after irradiation.[6] The wires were irradiated for $2\frac{1}{2}$ days at 50° C. to a burn-up of 10^{-6} of all atoms; this produced a steepening of the initial part of the stress/strain curve and the introduction of a fairly

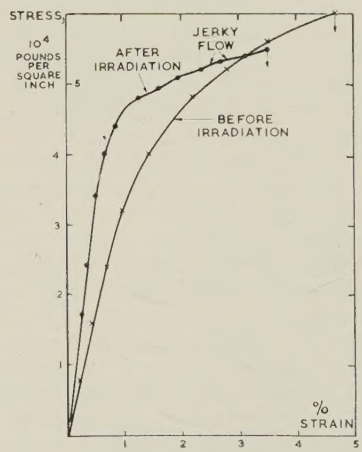

Fig. 1.—Stress/Strain Curves of Polycrystalline Uranium Wire Before and After Irradiation.

* "Burn-up" is defined here as the fraction of all the uranium atoms present that have undergone fission.

well-defined limit of proportionality. A change in mechanical properties of this magnitude in a non-fissile metal would require a fast-neutron irradiation of about 10^{19} nvt.[7]

When uranium is irradiated between 20° and 100° C. to a burn-up of 10^{-5}, it becomes completely brittle [4,8] and may crack in service owing to thermal or other stresses.

Changes in Physical Properties

The changes in physical properties of uranium under irradiation have not been studied systematically, but in power reactors the heat-flow from the fuel element needs to be very large, so that changes in thermal conductivity during burn-up are of practical importance. The thermal conductivity of uranium decreases by 10–15% both during and after irradiation.[9]

The electrical resistance of uranium increases by 1% after a burn-up [9] of 2×10^{-6} and by 4% for an unspecified burn-up at a temperature below 80° C.[8] The change in resistance was probably effectively saturated in both cases, and the final resistance depends largely on the temperature of irradiation. The extra resistance anneals out with an activation energy which increases with temperature [8] and finally reaches a value of 62·7 kg.cal./g.-atom, which is about the same as that for self-diffusion in uranium. This indicates that the extra resistance is not due to a random distribution of interstitials and vacancies, since it appears that the defects are removed only by the creation and diffusion of vacancies.

Growth and Wrinkling

Growth was an unexpected phenomenon that led to a large number of failures in early fuel elements based on wrought uranium. A burn-up of 10^{-4} may cause a uranium bar to increase in length by about 6%. The increase in length is proportional to the burn-up for small growths, while for large growths the logarithmic growth law is obeyed,[4] i.e. $\ln (L/L_0)$ is proportional to burn-up, where L_0 and L are the initial and final lengths (Fig. 2).

Growth consists of a change in shape without any change in volume. Single crystals of uranium increase in length in the [010] direction, decrease in length in the [100] direction, and remain unchanged in the [001] direction.[4,10] Experiments have shown [11] that uranium single crystals irradiated at 500° C. do not grow, although the α structure is stable up to 660° C. It has also been reported that growth is greatly reduced when uranium is irradiated in a liquid-air cryostat [4] and for a given burn-up growth is a maximum at about 200° C.

The principal texture of uranium bar rolled at 300° C. consists of grains with the [010] direction parallel to the axis, and since on irradiation crystals increase in length in the [010] direction, rolled bars also increase in length on irradiation. Rolling at higher temperatures in the α range results in a larger proportion of the texture with (110) planes normal to the axis; such material grows rather less for a given burn-up. The control of texture by control of the conditions of fabrication is difficult; fortunately, the preferred orientation can be almost entirely removed by heating the uranium into the β range (660°–770° C.).

Coarse-grained uranium wrinkles during irradiation. Bars made by casting or slow cooling from the β range undergo this type of distortion. Fig. 3 shows lead replicas taken from a heavily wrinkled bar after a burn-up of 6×10^{-4}. Wrinkling can be prevented by quenching from about 720° C. in the β range, a treatment which refines the grain structure.

Two types of mechanism have been suggested to explain the growth of uranium on irradiation. The first is based on the behaviour of a fission spike, that is, the small volume of material in which the fission energy is released. The expansion and contraction of the fission spike combined with the anisotropic plastic properties of α-uranium provide such a mechanism. The second type of mechanism is based on the anisotropic diffusion of the interstitials and vacancies produced by the fission fragments. Both types can be used to account for the change in growth rate with temperature,[10] and it has not yet been decided which is the correct one.

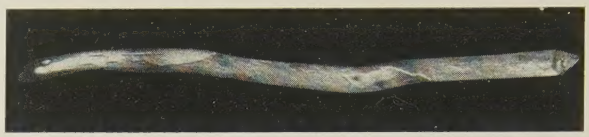

FIG. 2.—Uranium Specimen Consisting of Three Crystals Distorted After a Burn-Up of $2{\cdot}7 \times 10^{-4}$ at 200° C. × 3.

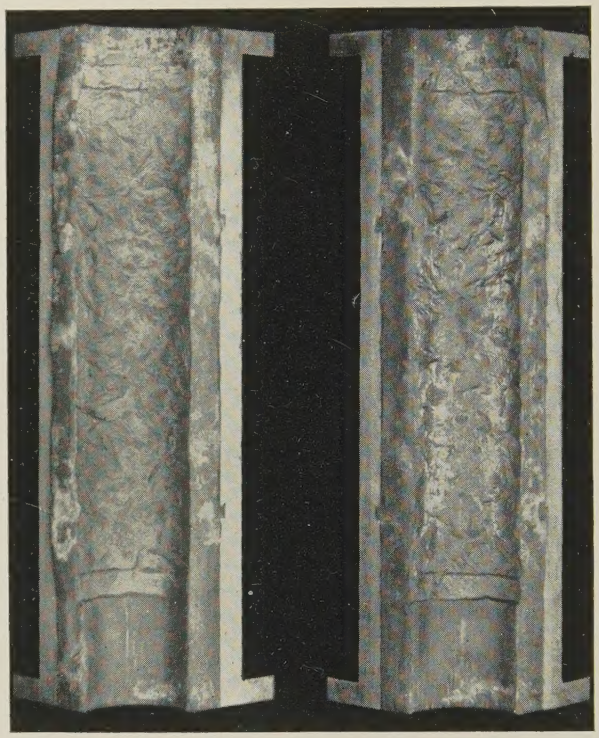

FIG. 3.—Lead Replicas Taken from a Coarse-Grained Uranium Bar After a Burn-Up of 6×10^{-4}. × ⅔. (Reduced by ¼ in reproduction.)

There are several indications that, with increase in perfection of the α-uranium single crystal, the growth for a given burn-up becomes less. Similarly, in textured bar, growth is greater the smaller the grain-size. The presence of dislocation arrays in the metal, therefore, seems to be an important factor influencing growth.

Swelling

At a burn-up of 10^{-3}, the presence of fission products themselves, especially the inert gases, causes large changes in structure and properties. At high temperatures, e.g. in the γ range (770°–1130° C.), the volatile fission products, particularly the inert gases, cause uranium to swell by forming gas bubbles in

the metal (Fig. 4). At lower temperatures, the chief effect of the fission products is to cause embrittlement; swelling does not occur below 300° C. except by the amount necessary to accommodate the extra number of atoms formed by fission.

Uranium Alloys

The irradiation behaviour of a number of uranium alloys has been studied in an attempt to discover a fuel element that prepared with either the α- or the β-uranium structure. Irradiation of this alloy in either form does not cause any change in structure,[9] although each atom is displaced from its lattice site a number of times. Failure to transform is probably due to the difficulty of forming a nucleus of the new phase. When uranium alloys consisting of two finely dispersed phases are irradiated at a temperature at which the two-phase mixture is the stable form, they are converted to the single-phase form which would normally be stable only at high temperatures.

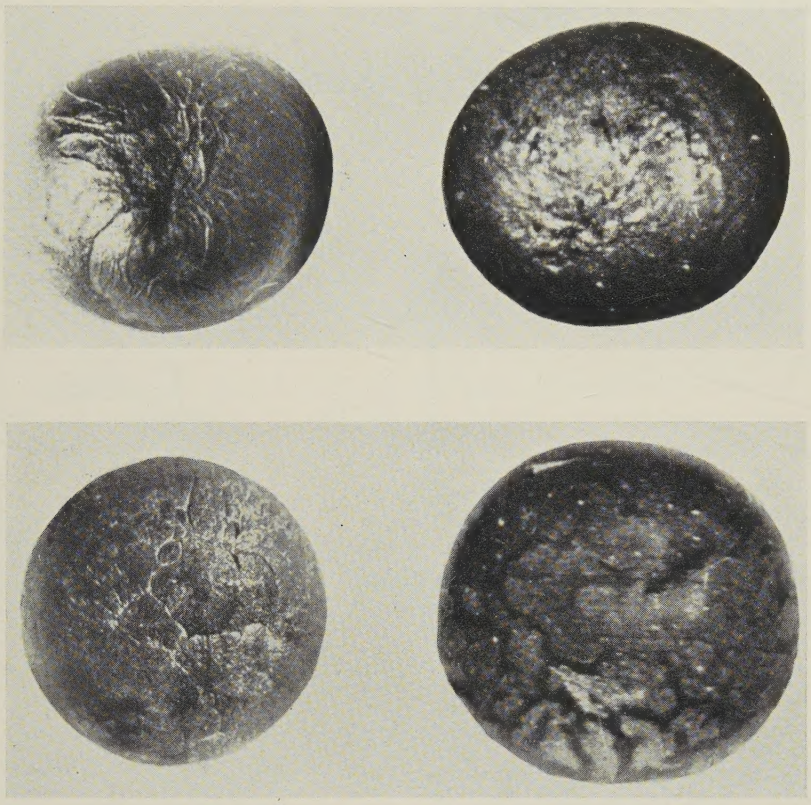

FIG. 4 (*a*)–(*d*).—Arc-Melted Pellets of Enriched Uranium Before and After Irradiation at a High Temperature. × 20.
(*a*) and (*b*) Density change 13%; (*c*) and (*d*) density change 38%.

will withstand a high burn-up while retaining its original dimensions. Small alloying additions of about $\frac{1}{4}$–$\frac{1}{2}$% can be used in conjunction with specific heat-treatments to give better grain refinement than that obtained by β quenching. Large additions of niobium and molybdenum have the effect of stabilizing the cubic γ phase of uranium, which does not suffer from growth or wrinkling.

A type of fuel element that will withstand a high proportional burn-up of the uranium is obtained by dispersing the latter in the form of intermetallic compounds or oxide in an aluminium matrix. It is claimed that such fuel elements give satisfactory service at temperatures up to one-third of the melting point of the matrix metal.[12] "Dilute" fuel elements can also be made by dispersing the uranium in the moderator, an example being UO_2 in graphite. The disadvantages of such an arrangement are the difficulty of chemical processing after irradiation and the large decrease in thermal conductivity of the graphite due to the action of the fission products.[9]

The stability of a number of uranium alloys under irradiation has been studied. Uranium plus 2% chromium can be Examples of this behaviour in uranium–molybdenum alloys [8] and uranium–niobium alloys [13] have been reported.

Conclusions

Effects observable in uranium at a burn-up of about 10^{-6} are not qualitatively different from those observed when non-fissile materials are irradiated with fast neutrons. At a burn-up of about 10^{-4}, gross changes in shape arise from the anisotropic nature of uranium; while at higher burn-up the fission products themselves cause changes in physical and mechanical properties and may cause gross damage such as cracking and swelling. While most of the changes are fairly well understood the exact mechanisms cannot be decided until more is known of the physics of the solid state.

Acknowledgements

The author wishes to thank his colleagues at Harwell for permission to refer to unpublished work.

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METALLOGRAPHIC METHODS FOR HIGHLY ACTIVE SPECIMENS

By P. C. L. PFEIL, Ph.D., B.Sc., Member

During the past three years, methods have been developed at the Atomic Energy Research Establishment for the metallographic examination of specimens having a high γ-activity. These methods are intended for activities up to 1 kilocurie, but so far results are available only on specimens of activities below 1 curie, prepared and examined in a small-scale temporary apparatus.

Nature of Specimens

The specimens were pellets weighing less than 0·5 g. enriched in the fissile uranium isotope U^{235} and irradiated until the order of 1 uranium atom in every 1000 had been converted into fission products. Since the polishing box had only a 2-in.-thick lead wall, several months' decay was needed to reduce the $\beta\gamma$ activity below 1 curie, the highest acceptable level.

Mounting

Two methods were developed for mounting the specimen in a suitable plastic; i.e. the preformed-mount and machine-moulded methods, as illustrated in Figs. 1 and 3. The mount components were machined from Perspex; the larger one (Fig. 1) was placed over the specimen, and a small amount of acrylic cold-setting plastic poured around the specimen. The

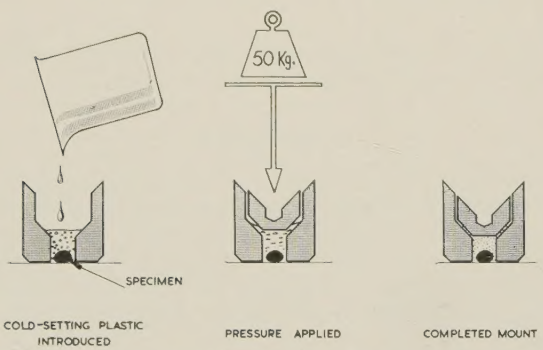

Fig. 1.—Mounting of Specimen in Preformed Mount.

small plug of Perspex was inserted, and pressure was applied with a remotely-operated hardness tester. The central hole in the plug was designed to suit the pin of the polishing machine.

In the machine-moulded method (Fig. 3), the specimen was centred by cam-operated levers on the table, which was then raised to mate with the Polythene ring, forming a circular mount into which cold-setting resin was injected with a syringe. The central hole reaching down to the specimen in

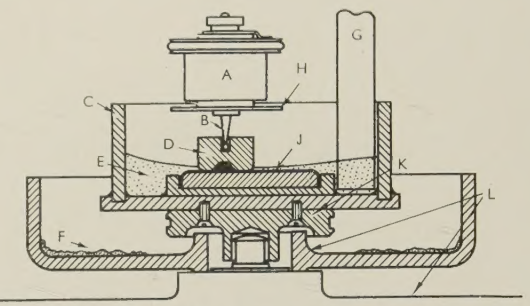

Fig. 2.—Attack-Polishing Bowl Fitted to an Automatic Polishing Machine.

Key.

A. Polishing head.
B. Stainless-steel pin.
C. Rotating Polythene bowl; welded construction.
D. Mounted specimen.
E. Acid solution and abrasive.
F. Sodium carbonate to prevent acid attack in case of spills.
G. Static Polythene anti-swirl plate.
H. Polythene splash disc.
J. Terylene-covered Polythene disc.
K. Standard 3½-in.-dia. brass lapping wheel.
L. C.T.S. automatic polishing machine.

the finished mount was convenient for the pin of the polishing machine and for a direct contact to the specimen for electropolishing.

Grinding and Polishing

Suitable laps made of plastic and silicon carbide or other abrasive have been developed for remote polishing and described by Haddrell, Sykes, and Mott.[1] These are normally used in conjunction with a polishing turntable specially designed for remote work, but in the temporary apparatus the laps were used on a Cooke, Troughton, and Simms polishing machine, the lap being changed at each stage of polishing. For final polishing, a Polythene bowl was fitted to the machine and the chromic acid/nitric acid/abrasive mixture used with a Terylene-covered Polythene wheel in the manner illustrated in Fig. 2.

Electropolishing techniques for remote operation have also been developed,[2] but were not incorporated here.

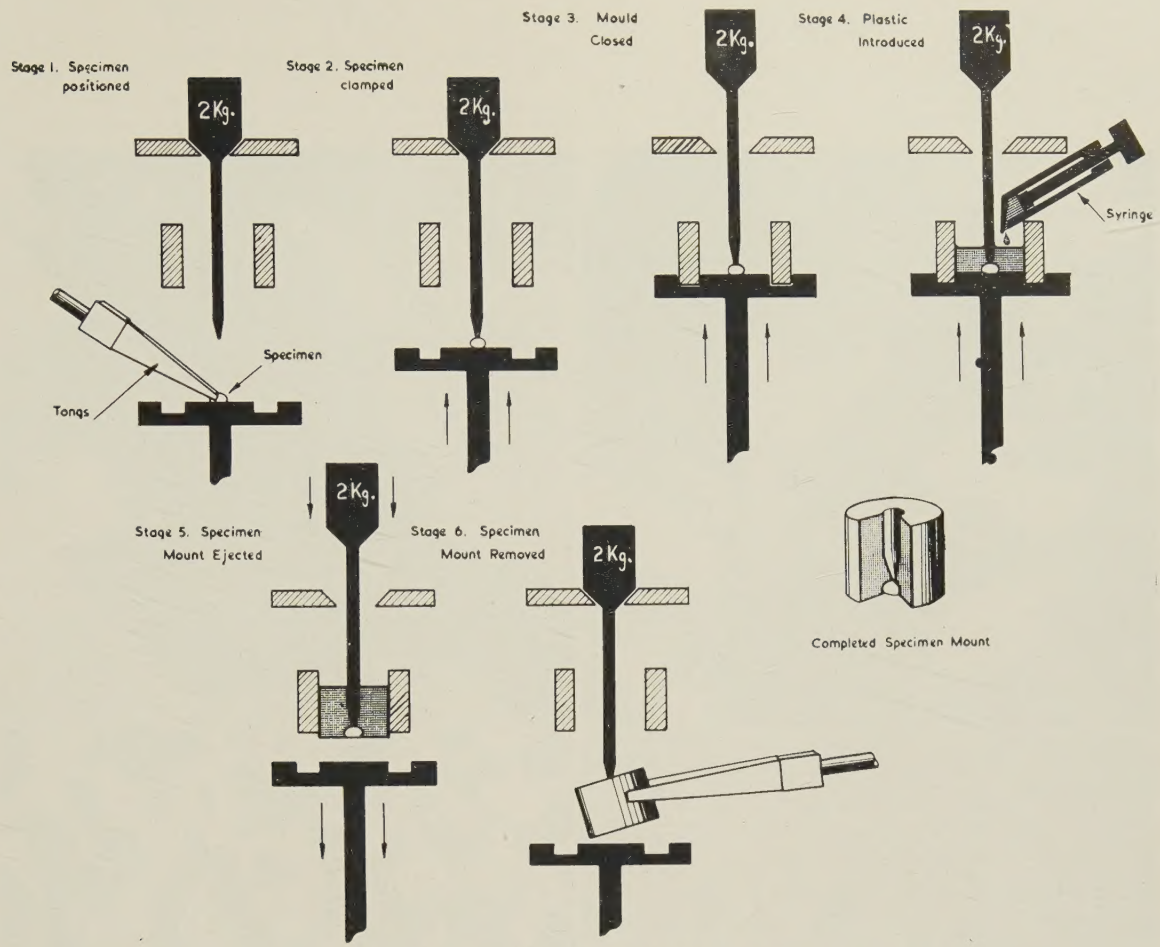

FIG. 3.—Operation of Automatic Mounting Apparatus.

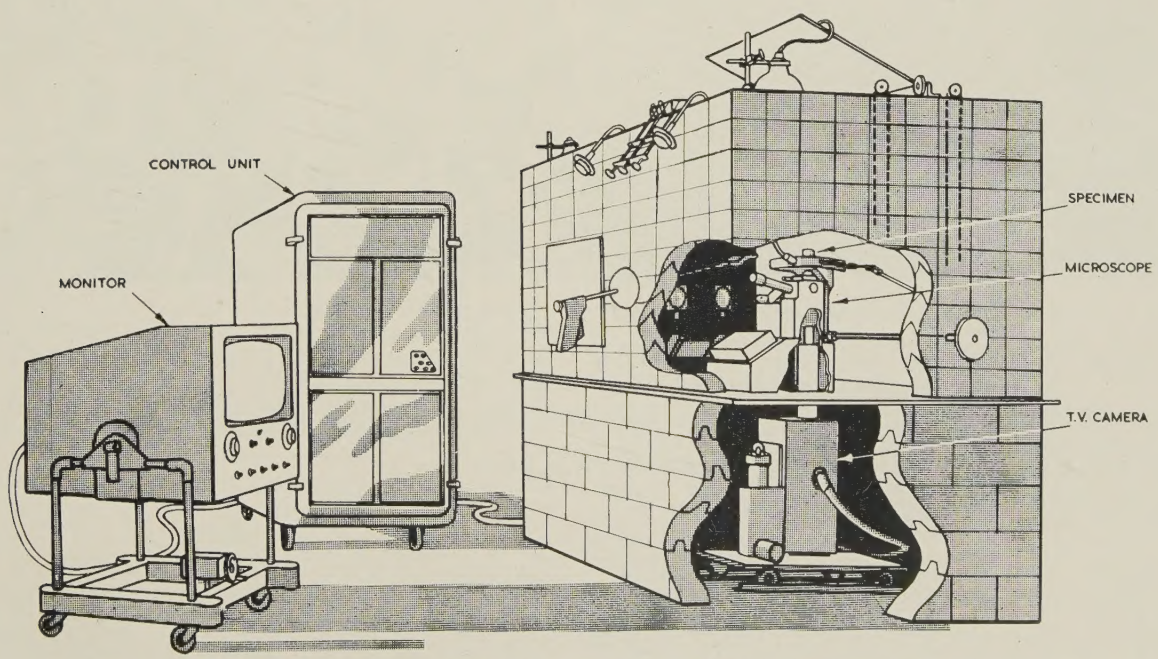

FIG. 4.—Arrangement of Microscope Box and Television Camera for Remote Viewing of Irradiated Specimens.

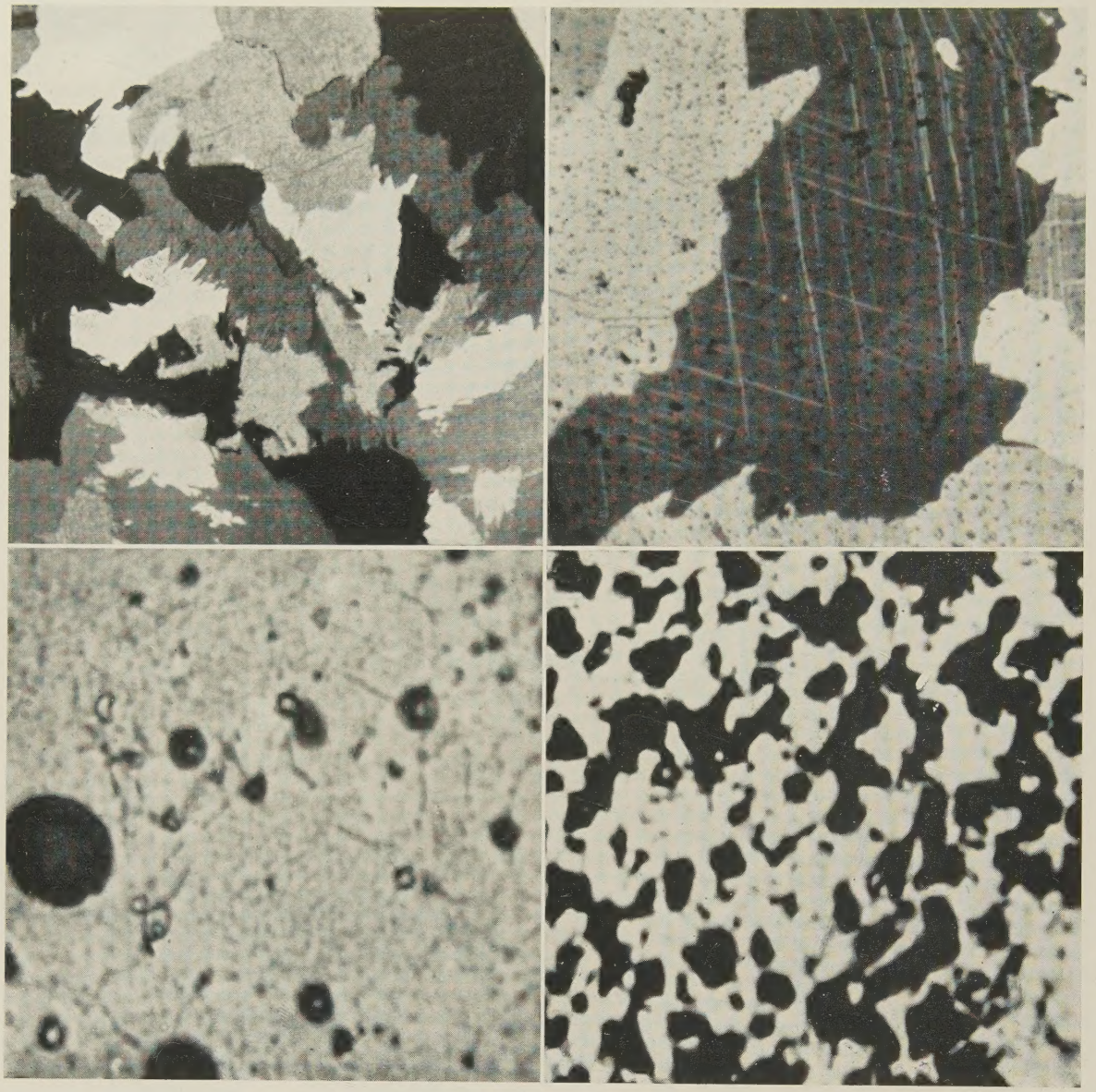

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FIG. 5.—Zirconium Under Polarized Light, As Viewed on Television Screen. × 125.

FIG. 6.—Uranium Under Polarized Light, Showing Twins. × 500.

FIG. 7.—Uranium Alloy Showing Irradiation-Induced Porosity. × 1250.

FIG. 8.—Porosity in a Uranium Alloy Sample Which Had Decreased 38% in Density on Irradiation. × 1250.

(All reduced by $\frac{1}{4}$ in reproduction.)

Microscope Cell

Specimens were transferred from the polishing cell to the microscope cell by long-handled tongs. The microscope box is illustrated in Fig. 4, which shows the pistol-grip tongs used to move the specimen on to the stage, and to change the objective of the Reichert microscope. Viewing was by a television camera using 625 lines, the image being displayed on a 15-in. screen. Because of the relatively long times required for the metallographic examination, 4-in.-thick lead walls were built up around the front and sides of the microscope. Remotely-operated controls included: coarse focus, fine focus, stage traverses, stage rotation, analyser, polarizer, aperture and field iris diaphragms, and filters. A plotter operated by the stage traverses was included so that maps could be made of the features of the specimens.

The definition obtained is illustrated by Figs. 5 and 6, which show unirradiated samples of zirconium and uranium polished by the same techniques and examined using the television equipment.

Examination of Irradiated Samples

It may be of interest to indicate briefly the results obtained on irradiated uranium samples. A feature of most microstructures examined was their lack of sharpness, persisting despite prolonged polishing. Similar unirradiated specimens prepared in the same way showed a crisp appearance. This false impression of inadequate preparation may be associated with strains in the material, presumably arising from the presence of fission products.

A second interesting feature was the rim of high porosity, about 0·5 mm. wide, found in certain specimens after irradiation at elevated temperatures; the pores were sometimes approximately spherical, as in Fig. 7, or irregular in shape, as in Fig. 8 (a different specimen).

A third outstanding feature was that irradiation seems to be able to induce phase changes from the normal α-uranium crystal structure, which is orthorhombic, to the γ, body-centred cubic modification. This has been found at the A.E.R.E. in uranium–niobium alloys and has also been reported by Russian workers in uranium–molybdenum alloys.[3] The mechanism is not known, but it may be connected with the locally melted regions (caused by fission spikes) not freezing back on the α lattice on cooling, if a suitable γ-nucleating agent is present.

Acknowledgements

The work described was performed at the Atomic Energy Research Establishment, Harwell, in the Metallurgy Division. The development of remote metallographic methods was initiated by Mr. B. W. Mott, and all the experimental work was carried out by Mr. E. C. Sykes and Mr. V. J. Haddrell. Thanks are due to Mr. I. A. Barwood for providing suitable irradiated specimens and for assistance in mounting them.

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PERSONAL NOTES

Dr. G. P. Conard has been appointed Associate Professor of Metallurgy and Director of the Magnetic Materials Laboratory, Lehigh University, Bethlehem, Pa., U.S.A.

Mr. J. R. Lee is now Development Metallurgist, Westland Aircraft Co., Ltd., Yeovil.

Mr. J. B. Marriott has been awarded the degree of Ph.D. of Glasgow University.

Mr. E. E. Schumacher, Metallurgical Director of Bell Telephone Laboratories, Murray Hill, N.J., has been awarded the honorary degree of Doctor of Engineering by the South Dakota School of Mines and Technology.

Dr. A. L. Sutton has left the R.T.S.C. Laboratories and taken up a position in the Metallurgy Department of the General Electric Company's Research Laboratories at Wembley, Middlesex.

Dr. H. E. Tuchschmid has joined the staff of the Research Laboratories of the Aluminium-Industrie A.G., Neuhausen-am-Rheinfall, as research physical metallurgist.

Mr. W. Udall has been appointed to the Board of the Brightside Foundry and Engineering Co., Ltd., Sheffield. He retains the title of Chief Engineer.

Death

The Editor regrets to announce the death of:

M. Albert Féron, Président et Administrateur Delégué de la S.A. Visseries et Tréfileries Réunies, at Ixelles on 2 July, aged 82. M. Féron was an Original Member of the Institute.

OBITUARY

Mr. R. W. Buzzard

Robert Walton Buzzard, a project leader for the Metallurgy Division of the National Bureau of Standards, Washington, D.C., died on 3 May 1956, at Ames, Iowa. Mr. Buzzard was attending a Metallurgy Information Conference of the Atomic Energy Commission at the time of his death.

Born in Fenton, Michigan, in 1904, Mr. Buzzard attended Michigan State College, from which he received the B.S. degree in Chemical Engineering and in Metallurgical Engineering. After graduation he was briefly employed in Detroit and with the Navy Department before joining the Metallurgy Division of the National Bureau of Standards in 1927. Mr. Buzzard worked on the development of anodic coatings for the protection of aluminium and magnesium alloys against corrosion, for which he obtained several patents. He also published papers on the spark testing of steels and on hydrogen embrittlement of steel.

His scientific research was interrupted by military service in the Ordnance Corps in World War II. He served in the African and European theatres and was awarded the Bronze Star before his discharge as a lieutenant colonel.

Afterwards Mr. Buzzard returned to the National Bureau of Standards and later supervised research on the development of constitutional diagrams of interest to the Atomic Energy Commission. His latest interests have been in the development of a unique approach to alloying theory by means of an ionic analysis method.

In addition to being a member of the Institute of Metals, he was a member of the American Society for Metals, the American Institute of Mining and Metallurgical Engineers, The Army Ordnance Association, The Electrochemical Society, and Alpha Chi Sigma.

OTHER NEWS

Expansion of Metallurgy at Oxford

At a meeting of Congregation on Tuesday, 12 June, a statute was promulgated which added the Science of Metals to the list of subjects that may be offered by candidates in the Honour School of Natural Science at Oxford.

This subject covers much of the ground that is covered by those who offer chemistry in that Honour School. The amount of organic chemistry, however, has been reduced in order to provide room for the science of metals.

The new course is divided into Parts I and II on the same lines as the chemistry course, and in Part II a candidate will submit a thesis on a metallurgical subject after spending a year on research. Classified honours will be awarded on the combined results of both parts.

The new course marks a further stage in the development of metallurgy at Oxford which follows the establishment of the George Kelley Readership by the Pressed Steel Co., Ltd., and the appeal for funds for the subject which was strongly supported by the late chairman of the Company, Major Albert Pam.

Post-graduate research work in metallurgy has been carried out at Oxford for more than 30 years under Dr. W. Hume-Rothery, O.B.E., F.R.S., in the Inorganic Chemistry Laboratory, where its development owes much to the interest of Professor Sir Cyril Hinshelwood, F.R.S.

An independent Department of Metallurgy under Dr. Hume-Rothery is now being set up in temporary accommodation, and it is hoped that a new laboratory will be built within the next few years.

The new development is particularly welcome in view of the close association of Oxford with metal-using industries.

APPOINTMENTS VACANT

ASSISTANT METALLURGICAL CHEMIST, male, required for new works laboratory. Apply to Metals and Methods, Ltd., Langley, Slough, Bucks.

HADFIELDS, LTD., invite applications from young men with qualifications preferably in metallurgy, or alternatively in physics, to fill a senior post in the Radiography Section of the Research Department. The position offers attractive prospects in an expanding department concerned with a variety of problems, ranging from inspection and quality control to the development of new techniques in the production of steel castings of all types and sizes. Commencing salary according to qualifications and experience. Applications should be addressed to the Personnel Manager, Hadfields, Ltd., East Hecla Works, Vulcan Road, Sheffield 9.

INDIAN INSTITUTE OF SCIENCE
BANGALORE 3
INDIA

Applications (six copies) on the prescribed form obtainable from the undersigned on payment of Re. 1 per set either by money order or by postal order are invited not later than the 23 September 1956, for the post of PROFESSOR AND HEAD OF THE DEPARTMENT OF METALLURGY AT THE INSTITUTE in the grade Rs.1000-50-1500. Such special pay in the case of a candidate with exceptionally high qualifications and an overseas allowance not exceeding Rs.500 p.m. in the case of a foreign national as may be decided upon by the authorities of the Institute may be sanctioned. Further details can be had on request.

QUALIFICATIONS: High academic qualifications with wide experience in research, teaching, and industrial processes.

DUTIES: (*a*) Instruction of students in metallurgy; (*b*) conduct and guidance of research; and (*c*) administration of the Department of Metallurgy.

A. G. PAI,
Registrar.

G.K.N. GROUP RESEARCH LABORATORY invites applications from METALLURGISTS, PHYSICISTS, or PHYSICAL CHEMISTS to work on the problems detailed below.

1. The galling and surface binding of titanium and its alloys.
2. The development of vacuum-casting techniques and the investigation of the effect of vacuum casting on the properties of high-temperature and other special-purpose alloys.
3. The creep testing of commercial forgings, or experimental cast alloys, and the development of design curves for the latter.
4. The improvement of industrial processes, with particular reference to the surface finish of the deposit.
5. The constitution and heat-treatment of silicon–iron alloys.
6. The study of recrystallization and grain growth and their effect in orientation development in silicon-iron alloys.

The Laboratory is the Central Research Establishment for a large Group of Companies engaged in a wide range of metallurgical and engineering activities. It is housed in modern buildings well equipped for both fundamental and development research. There is every opportunity for contact between the Laboratory and production units. The activities of the Laboratory are expanding and future prospects are excellent.

Applicants should possess a first- or second-class degree in the appropriate subject and preferably have had at least two years' research or industrial experience, although this need not be in the stated field.

Applications should be made to the Director of Research, G.K.N. Group Research Laboratory, Birmingham New Road, Lanesfield, Wolverhampton.

METALLURGIST required, Birmingham District, to take charge of Laboratory and Heat-Treatment Department of Light Engineering Works under direction of Chief Metallurgist. A.I.M. minimum standard required, with experience of tool, ferrous, and light-alloy heat-treatment. Investigations of works production problems form an important part of this situation. Knowledge of tungsten carbide technology an advantage. Write, giving full details of age, qualifications, salary required, &c., to Box No. 410, Institute of Metals, 17 Belgrave Square, London, S.W.1.

METALLURGISTS. Applications are invited for posts in an expanding group concerned with the design of Nuclear Power Plant. Successful candidates will have the opportunity to work on a variety of projects in the fields of metal fabrication, melting, and welding. Practical experience in one of these fields is desirable. These positions offer scope for initiative, and staff are encouraged to assume responsibility. Salary will be in accordance with qualifications and experience. Apply giving full details of training and experience to Personnel Manager, (N.P.), The General Electric Company, Ltd., Fraser & Chalmers Engineering Works, Erith, Kent.

OLD-ESTABLISHED NON-FERROUS METALS MANUFACTURERS in S.W. Lancashire require qualified Metallurgists for Process Control. These vacancies are particularly suitable for young men who have completed, or are about to complete, their National Service. Applicants should write stating details of education and qualifications to Box No. 409, Institute of Metals, 17 Belgrave Square, London, S.W.1.

UNIVERSITY OF BIRMINGHAM

DEPARTMENT OF INDUSTRIAL METALLURGY

Joseph Lucas Research Fellowship

Applications are invited for the above Fellowship, which will be vacant from 1 October 1956. The successful candidate, who should possess an honours degree in metallurgy, chemistry, or physics, will be required to investigate the structure and metallurgical properties of electrodeposits. The salary will be in the range £600–£850 per annum. Applications should be submitted as soon as possible to the Registrar, the University, Birmingham 15.

G. L. BARNES,
Secretary.

UNIVERSITY OF BIRMINGHAM

DEPARTMENT OF PHYSICAL METALLURGY

Applications are invited for a Lectureship (Grade II) in Physical Metallurgy. The salary will be in the range £650–£1350 (with efficiency bar at £900) per annum according to qualifications and experience. The successful candidate will be expected to take up his duties on 1 October 1956. Applications should be sent as soon as possible to the Registrar, the University, Birmingham 15, from whom further particulars may be obtained.

G. L. BARNES,
Secretary.